Solar-Thermal Activation of Rear-Ventilated Façades as a Source for Heat Pump Based Heat Supply Systems

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Abstract

The envelope of multi-storey residential buildings offers an untapped potential for the integration of regenerative energy supply systems. Due to their specific assembly, rear-ventilated façades exhibit particularly suitable features: high design flexibility, modularity, easy installation and maintenance, and the possibility to hide the systems engineering in the ventilation gap. We analyzed solar thermally activated façade claddings made of concrete focusing on their thermal performance. Based on these results, the potential of the concrete façade as an additional source in a ground source heat pump system is assessed by building simulations with the software TRNSYS. A comparison of different heating systems shows that for a multi-storey building of about 1400 m² living space with an opaque wall area of nearly 1010 m², a 75 m² light grey concrete façade can reduce the borehole heat exchanger (BHE) by 25% to 600 m without a reduction of performance thanks to active regeneration. In addition, the façade can be used to further heat the BHE outlet. Significantly higher efficiency is expected for larger areas and better performing façade claddings in combination with different operation modes.

Keywords: rear-ventilated façades, solar thermal collectors, TRNSYS, multi-storey residential buildings, heat pump, building envelope, building integration

1. Introduction

To reduce both energy demand and CO_2 emissions, it is necessary to significantly increase the use of renewable energies and implement more severe energy efficiency measures. For this purpose, EU directives and national laws are tightening the requirements for existing and new buildings, focusing on higher renovation rates and a more effective substitution of fossil fuels. The combination of solar-thermal energy and heat pump can make a decisive contribution towards a climate neutral heat supply. Whereas both technologies are already well established in the sector of single-family houses, there is a lack of economical and architecturally appealing solutions in the field of multi-family buildings. The most critical points for heat pumps are noise emissions in the case of air-water systems and a lack of space for suitable heat sources in the case of ground source systems. For solar-thermal energy usual factors include a limited space for solar collectors, costs, and the technically complex implementation.

2. Solar-thermal activation of a building envelope

Façade-integrated solar-thermal collectors offer untapped potential for the implementation of new, aesthetically appealing solutions for multi-family buildings. Rear-ventilated façades are particularly suitable for solar-thermal activation due to their advantages in terms of building physics, modularity, and the large number of cladding materials that can be used. Furthermore, the ventilation gap between the façade cladding and the mineral insulation of the building provides enough space for the invisible installation of the components of the system. In the scope of a current research project, different concepts for thermally active rear-ventilated façades are being developed and the energy potential of the façades as alternative or additional heat sources in heat pump-based heat supply systems is being evaluated experimentally and theoretically (Frick, Büttner, et al., 2021). The basic approach consists in activating the façade using components that are already available on the market without modifying their original appearance so that the active modules cannot be distinguished from the common ones. As façade

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claddings, concrete, metal, and glass (single- and double-glazed) are investigated. For each material, specific activation approaches were chosen (Frick, Kirchner, et al., 2021). To evaluate the behavior of the investigated façade types as part of the heat supply system of a multi-family building, system simulations using TRNSYS (Klein, 2010), a simulation program used in the fields of renewable energy engineering and building simulation with a focus on active and passive solar use, were carried out. The experimental investigations and numerical modeling of the different facade panels were used to determine the collector parameters. According to the collector equation *(eq. 1)* used in TRNSYS Type 832 by Haller et al. (2014), the relevant collector parameters were determined and are shown in Tab. 1 (see appendix for an explanation of the used quantities). As a reference, a typical flat plate collector (Solar Keymark Database, 2019) both for rooftop and façade installation is included. For the façade collector, the heat loss coefficient a_1 is reduced, to account for the lower convective heat transfer in a vertical air gap (Bartelsen et al., 1999).

Tab. 1: collector parameters, based on gross area

		façade cladding				**collector**	
Parameter	**Unit**	**Concrete**	**Metal**	**Glass unglazed**	**Glass double-glazed**	**Flat Plate Tilt 45°**	**Flat Plate Tilt 90°**
η_0, $F'(\tau\alpha)$	-	0.40	0.59	0.774	0.58	0.78	0.78
b_0	-	0.055	0.055	0.055	0.081	0.13	0.13
K_{diff}	-	1	0.98	1	0.86	0.88	0.88
a_1	$W\ m^{-2}\ K^{-1}$	11.30	11.33	9.33	4.982	3.35	3.05
a_2	$W\ m^{-2}\ K^{-2}$	0	0	0	0.0212	0.013	0.013
a_3, $c_{w,hl}$	$J\ m^{-3}\ K^{-1}$	4.04	1.22	3.74	0	0	0
a_4, c_{IR}	-	0.761	0.212	0.691	0	0	0
a_5, $\mathrm{C_{eff}}$	$J\ m^{-2}\ K^{-1}$	282000	22755	11000	23060	6220	6220
a_6, $\mathrm{c_{wF'}}$	$s\ m^{-1}$	0.056	0.0144	0.0224	0	0	0

$$\dot{q}_{out} = F'(\tau\alpha) \cdot K_b \cdot I_b + F'(\tau\alpha) \cdot K_d \cdot I_d - c_{w,F'} \cdot u_w \cdot (I_b + I_d) + c_{IR} \cdot (I_{IR} - \sigma \cdot T_{amb}^4) - a_1 \cdot \Delta T_{amb} - a_2 \cdot |\Delta T_{amb}| \cdot \Delta T_{amb} - c_{w,hl} \cdot u_w \cdot (\Delta T_{amb}) + \dot{q}_{lat} - C_{eff} \cdot \frac{d\vartheta_m}{dt} \qquad \text{(eq. 1)}$$

with

$$\Delta T_{amb} = \vartheta_\mathrm{m} - \vartheta_\mathrm{amb};\ u_w = wf \cdot \mathrm{u_{w,0}};\ I_{IR} = rf \cdot I_{IR,0} + (1 - rf) \cdot \sigma \cdot T_{amb}^4$$

The potential of the thermally activated façade can be estimated by a heat yield investigation. For a constant inlet temperature, the yield is determined depending on weather data and orientation and is plotted in Fig. 1. A demonstration building with a solar active concrete façade is planned in Pforzheim, Southern Germany, therefore weather data for the corresponding location are used. The data were taken from Meteonorm, using the Hofmann model hourly values are converted into minute values (Meteotest, 2022; Hofmann et al., 2014). Compared with a common flat plate collector mounted on the roof, the façade cladding acts as an uncovered collector (or WISC, Wind and Infrared Sensitive Collector) and allow the use of environmental heat at low temperatures.

The operation temperature of the façade must be taken into account. Operation at low temperatures promises high yields because a lot of environmental heat can be gained. However, dew formation or even icing may occur which can be undesirable due to algae formation and optical changes of the concrete surface. Other materials (e.g., metal) might be better suited to withstand lower temperatures and exhibit a higher potential for this application. To use the façade as a source for the heat pump, the operating limits of the evaporator side must be taken into account. Other use cases for the façade are the regeneration of the borehole heat exchanger and, at suitably high temperatures, the direct loading of the buffer storage tank. However, high temperatures must be reached, façade claddings like glass, especially the double-glazed design, or metal are suitable for this.

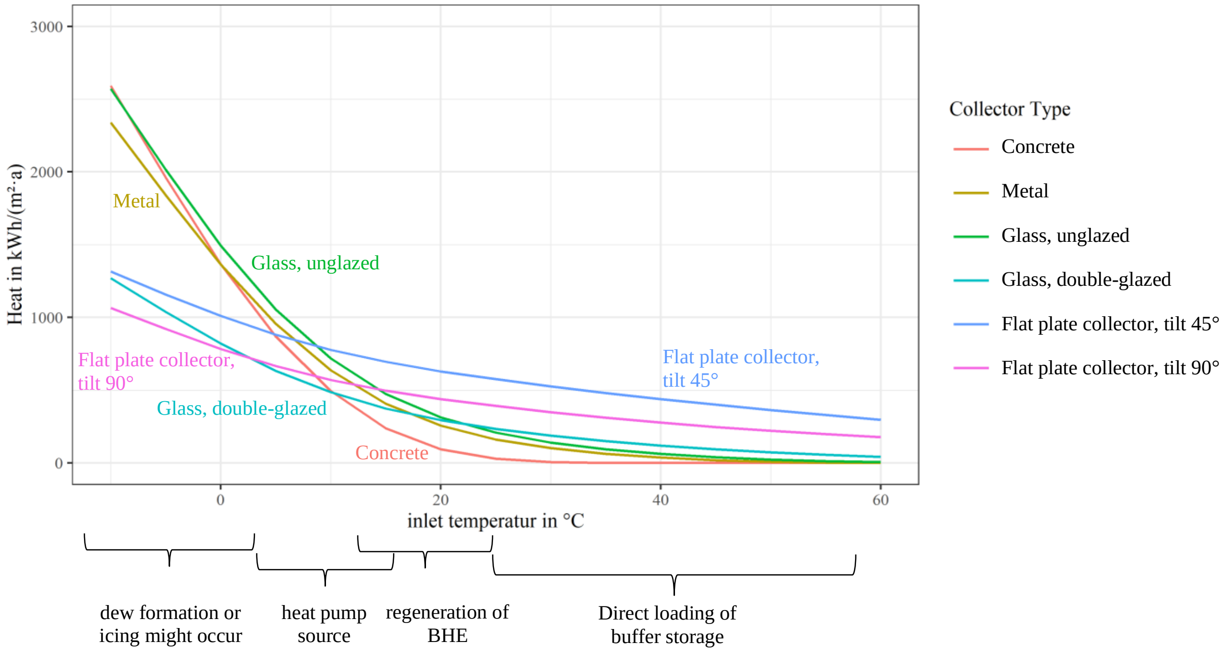


Fig. 1: yearly gross heat yield of different façade claddings (concrete, metal, glass, insulated glass) and rooftop collector facing West for constant inlet temperatures and possible application fields

The temperature range between 5 and 25 °C is well suited as a supplementary heat pump source. At higher temperatures (e.g., 15 to 28 °C) regeneration of the ground source (e.g., borehole heat exchanger) of the heat pump becomes possible. Due to the arrangement (façade, vertical alignment) and thermal characteristics, the yield is low at even higher temperatures. Thus, both the lower and upper limits might be fixed, depending on the heating supply concept and operation mode. With higher operating temperatures the yield decreases and thus the contribution of the facade to the overall system.

The distribution of the heat output in the annual and daily course for differently oriented concrete façades for 5 and 20 °C inlet temperatures is shown in Fig. 2.

At low temperatures, the façade can supply useful heat throughout the year, but its operation at higher temperatures is only possible in transition and summer periods. Because the façade also acts as an environmental heat exchanger, in summer useful gains with over 200 W/m² are possible even at nighttime. Depending on the orientation of the facade, the maximum values are reached in the morning hours (facing east), at midday (facing south), or in the afternoon hours (facing west).

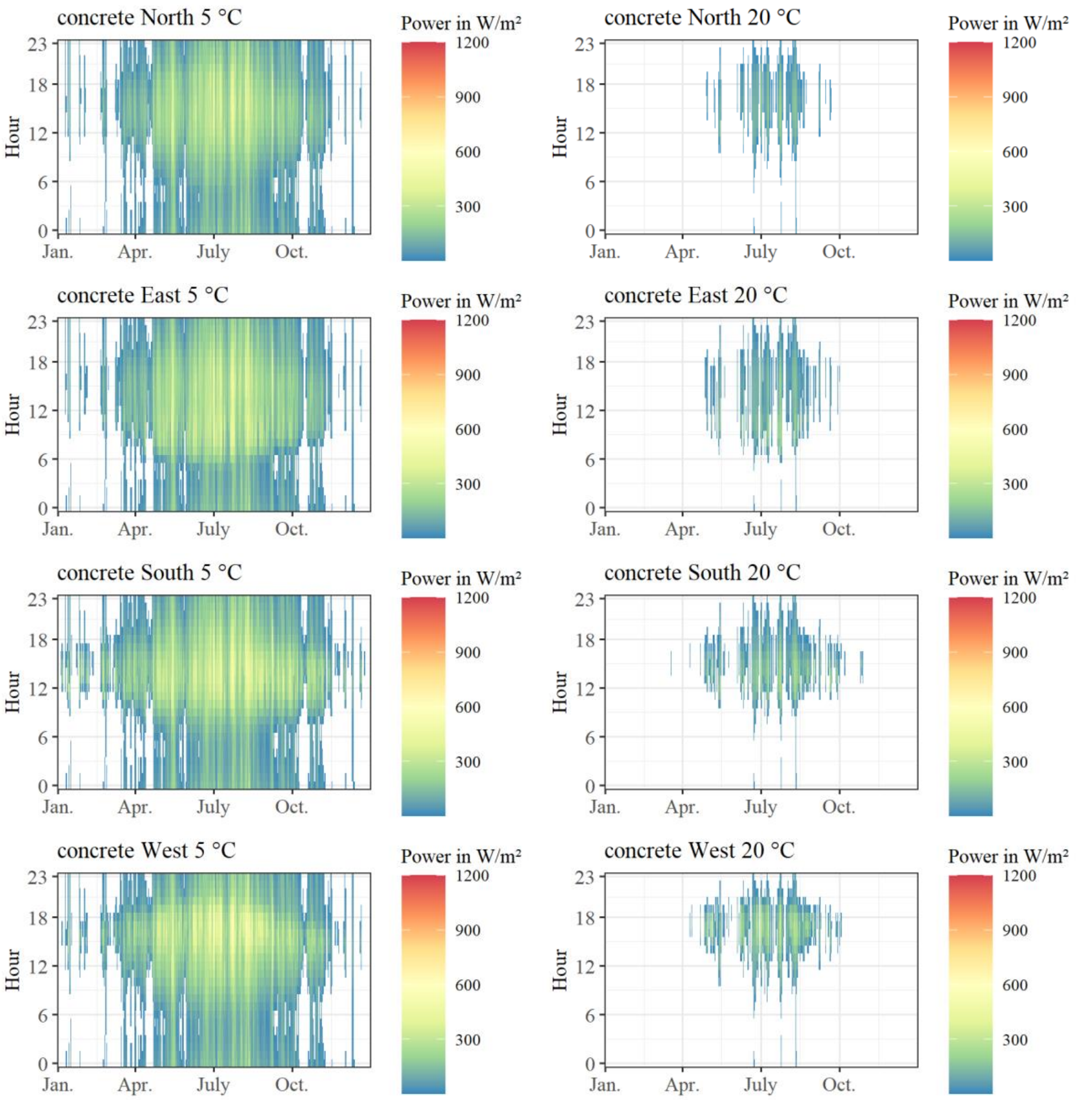


Fig. 2: annual and daily distribution of heat flux for the concrete façade facing different directions at a constant inlet temperature of 5 and 20 °C

3. System Concept

The heat for the investigated multi-storey residential building is primarily generated by a brine-to-water heat pump and stored by using the thermal mass of the building as well as a common buffer storage. The façade serves as a solar collector and environmental heat exchanger. The gained energy can be used in different ways, depending on the system configuration: it allows the regeneration of the borehole heat exchanger, heats the ground source outlet, or can be directly used for the heat pump as an additional source. The investigation aims to assess the potential of the façade as a heat pump source, depending on its characteristic performance values and the specific function. Fig. 3 shows the general scheme of the investigated system.

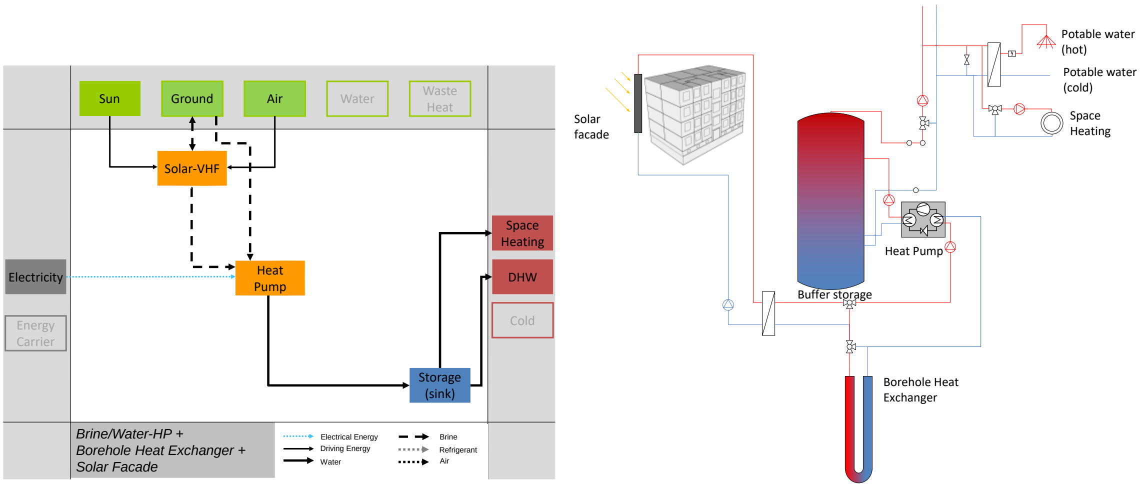
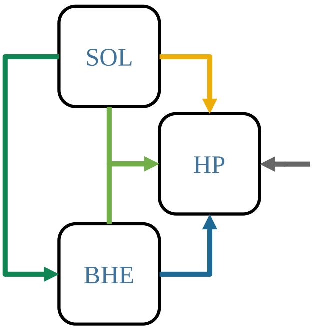


Fig. 3: Left: Schematic of energy flows in the investigated heat supply system (green: environmental energy, orange: energy conversion, blue: thermal energy storage, red: useful energy). Right: Schematic diagram of the heat supply system under investigation

Using TRNSYS, a multi-family building, consisting of 19 apartments each with 84 m² net space was modeled using Type 56. The heat demand of the building is 52.5 MWh/a, with an additional hot water demand of 19.5 MWh/a (Jordan et al., 2019). The building heat supply system consists of a modulating brine-water heat pump (Type 401), the solar-thermal active façade with heat exchanger (Type 832 by Haller et al., 2014), a borehole heat exchanger (Type 346), a centralized 2000 l buffer storage (Type 340) and decentral instantaneous water heaters in each apartment. The brine-water heat pump uses mainly the borehole heat exchanger as a heat source and loads the buffer storage so that a supply temperature of 35 °C is available at the instantaneous water heaters. The decentralized stations use this supply temperature directly for the floor space heating. Via a heat exchanger and an additional electric rod, the potable hot water (45 °C) is produced directly according to demand and in a hygienic manner. The façade is used as an additional source as long as the outlet temperature is above 5 °C (to reduce dew formation and prevent icing) and below 25 °C (max. inlet temperature of heat pump source side). For façade outlet temperatures above 11 °C, the borehole heat exchanger as a source is deactivated. Additionally, the façade enables the regeneration of the borehole heat exchanger, ensuring their sustainable operation and offering the possibility to significantly reduce their size. For a visualization and explanation of the different energy flows see Fig. 4.



SOL -> BHE:	Solar façade (SOL) for active regeneration of Borehole Heat Exchanger (BHE)
BHE + SOL -> HP:	Outlet of BHE additionally heated by SOL as a source of a heat pump (HP)
SOL -> HP:	SOL as a source of HP
BHE -> HP:	BHE as a source of HP
-> **HP**:	Power consumption of HP compressor

Fig. 4: Color-coded energy flows with description

4. Results

The system with the thermally activated concrete façade is compared with a common system consisting of a gas boiler or brine-water heat pump. According to the requirements of the German building energy act (GEG, 2020), a heating system with fossil energy sources needs a share of renewable energy sources, therefore the system with a gas boiler includes a suitably dimensioned solar thermal collector (COL) for direct loading of the storage (ST). The systems are described in the following and the results are shown in Fig. 5. The area of the active façade is based on the plan for the demonstration building.

1. HE + COL: Gas condensing boiler with solar support (35 m² flat plate collectors with south orientation and 45° inclination).
2. HP + BHE: brine-water heat pump with ground source (8 x 100m borehole)
3. HP + SOL + BHE (red.): like 2, but additionally with solar thermal activated façade (75 m² east and 25 m² west) and a reduction of the number of boreholes by 25% (6 x 100 m)

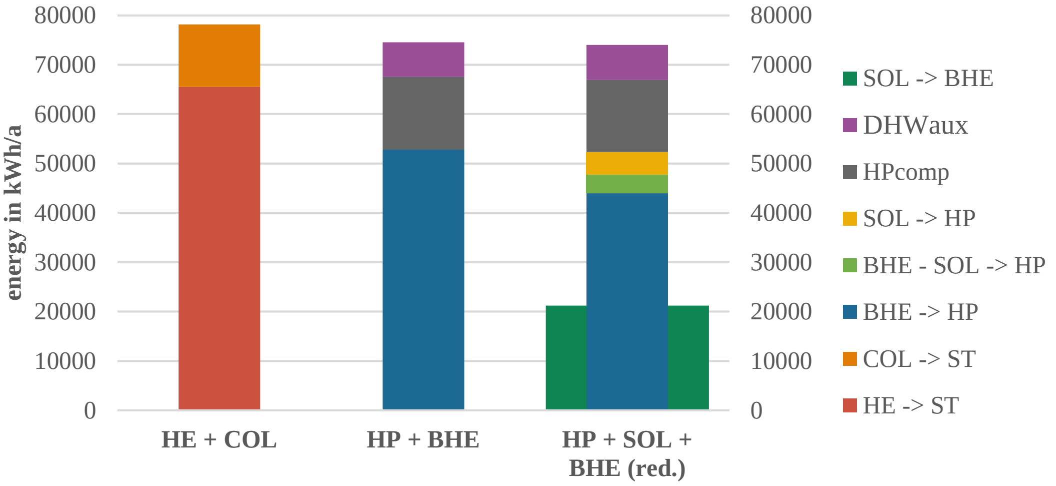


Fig. 5: Representation of the energy flows for 3 heat supply concepts

In addition to the energy flow and its color coding, already described in Fig. 4, the figure also shows the power consumption of the heat pump compressor (HPcomp) and the electric heating of domestic hot water in the instantaneous water heater (DHWaux). The sum of the heat quantity of the different sources, as well as the electricity consumption less the system losses (storage and distribution losses) results in the useful heat quantity of approx. 72 MWh/a.

The gas boiler supplies the buffer storage with approx. 65 MWh/a and the roof-mounted flat plate collector supplies 13 MWh/a heat to cover the useful heat demand. No additional electrical heating through the instantaneous water heater is needed (HE + COL).

The heating systems with a heat pump are using a lower set temperature in the buffer storage, which improves the efficiency of the heat pump and reduces the system losses. But additional electrical heating (approx. 7 MWh/a) is required for the domestic hot water preparation. The heat input to the storage tank is reduced to approx. 68 MWh/a of which approx. 53 MWh/a are drawn from the borehole heat exchanger (HP + BHE).

The use of the thermally activated building envelope in combination with a 25% smaller ground source can reduce the heat extraction from the ground to 44 MWh/a. More than 8 MWh/a from the facades are used as a heat pump source. In addition, more than 21 MWh/a are used to regenerate the borehole heat exchanger, which reduces the drop in ground temperature during the operating time and also ensures high annual performance factors after decades of operation (HP + SOL + BHE (red.)).

Tab. 2: Annual performance factor for different heat supply concepts, calculated as the ratio of condenser output to work of the compressor

HEATING CONCEPTS		SPF
2:	HP + BHE (8x 100 m)	4.58
3:	HP + BHE + SOL (6x 100 m)	4.60

As a result, the borehole heat exchanger field can be reduced by 25% with the support of a relatively small solar-activated façade without a reduction of the heat pump's performance (see Tab. 2). Using Earth Energy Designer

(Hellström and Sanner, 2000), the influence of the regeneration on the ground temperatures over several years can be calculated. Using the results of the system simulation, the unloading and loading of the borehole heat exchanger were used for the simulation of the BHE and ground temperature for a period of 35 years.

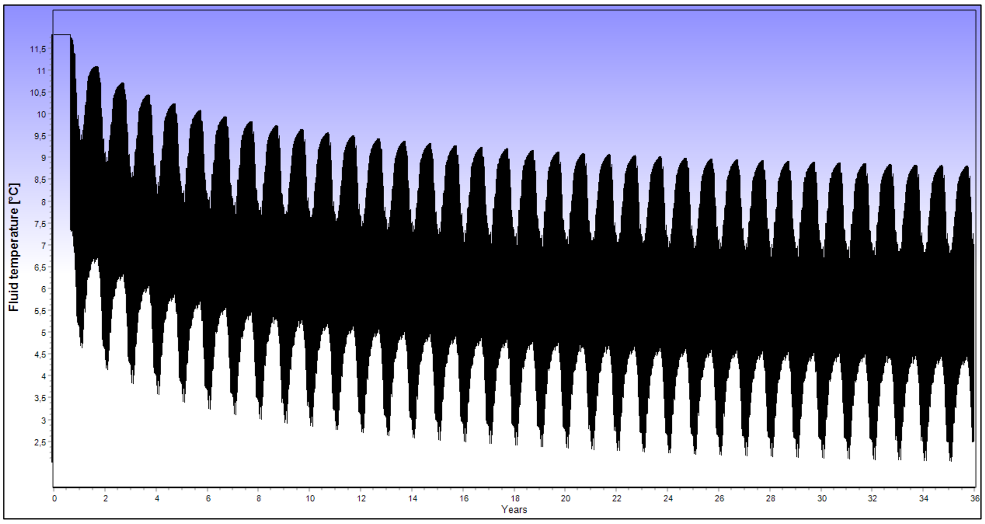


Fig. 6: mean fluid temperature of the borehole heat exchanger (8x 100m) during 35 years for the concept HP + BHE

In the system without active regeneration, the ground temperature and thus also the fluid temperature of the borehole heat exchanger decreases in the first years of operation. The temperature drop amounts to approx. 2.0 K after 10 years, and 2.5 K after 35 years (see Fig. 6).

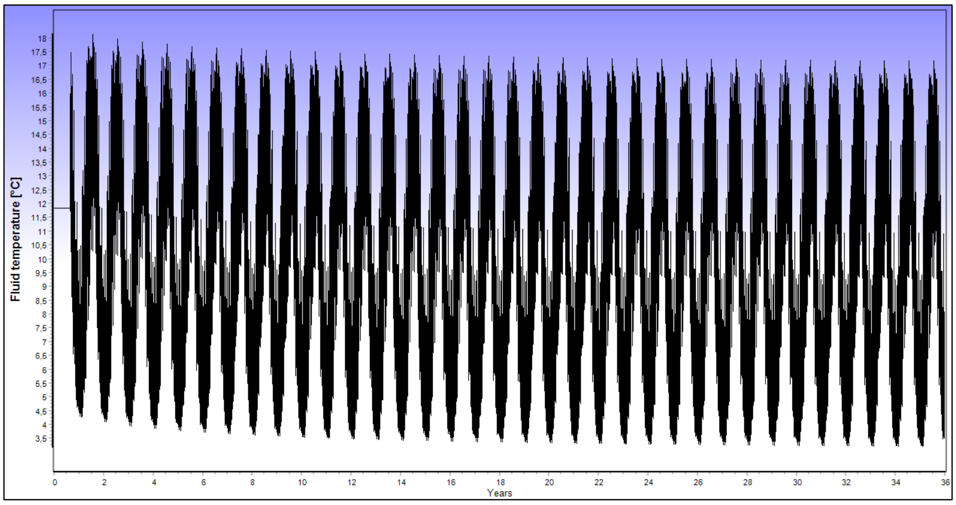


Fig. 7: mean fluid temperature of borehole heat exchanger (6x 100m) during 35 years for concept HP + BHE + SOL

Due to the active regeneration of the BHE (see Fig. 7), the cooling effect of the fluid during the operating time is lower, and the temperature does not decrease further after the first years. The temperature drop amounts to approx. 1.0 K after 10 years, and 1.2 K after 35 years. In addition, high temperatures of up to 17 °C are available after active regeneration, thus even with a reduced ground source, a higher heat pump performance is still reached.

4.1 Façade orientation

Fig. 8 shows the influence of the different orientations of the solar façade. In each case, 75 m² of the solar thermally activated concrete façade are considered for either the north, east, west, or south façade.

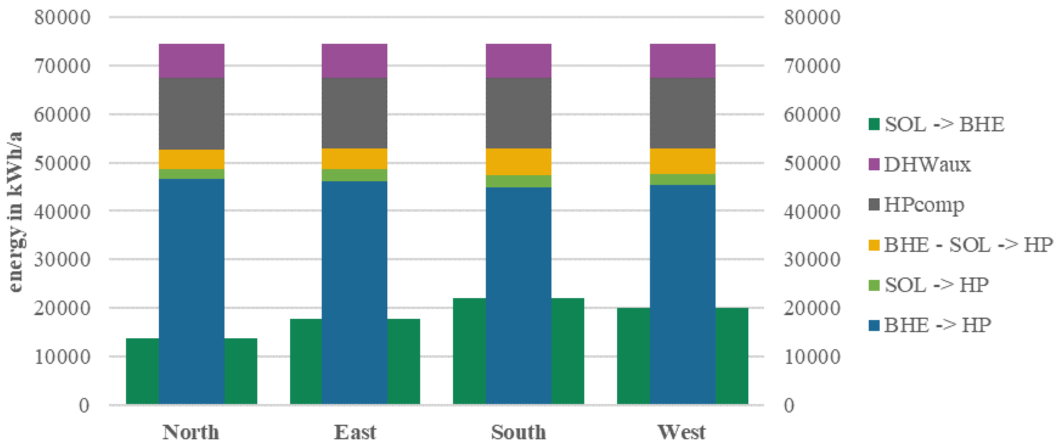


Fig. 8: Distribution of the heat yields of a 75 m² concrete facade for different orientations

The orientation has a significant influence on the yields of the façade, especially for the active regeneration of the borehole heat exchanger field. For this operation mode, the solar thermal activated facades serve both as environmental heat exchangers and solar collectors.

Tab. 3: yield of the concrete façade for different operation modes

				without regeneration (without SOL->BHE)		with regeneration (with SOL -> BHE)	
orientation	**SOL -> BHE**	**SOL -> HP**	**BHE + SOL -> HP**	**in kWh/a**	**in kWh/ (m²a)**	**in kWh/a**	**in kWh/ (m²a)**
North	13659	4017	2148	6165	82	19824	264
East	17766	4321	2391	6712	89	24478	326
South	21972	5363	2657	8020	107	29992	400
West	19973	5233	2225	7458	99	27431	366

To meet the increased demand for heat and daylight in living and recreational rooms, these are often orientated to the south. Although this orientation is also advantageous for the solar facade (see Tab. 3), solar thermal activation of a larger contiguous opaque area is often not possible due to the interruption by windows. For this purpose, especially in freestanding buildings, the facade areas with west and east orientation are better suitable. A solar facade with a west orientation has higher yields compared to an east facade. The east facade can gain energy from solar radiation in the morning hours but is at a lower temperature level overall due to its thermal capacity and the low outdoor temperatures at night. The west façade heats up over the course of the day and reaches its highest temperatures during the afternoon and evening hours. In addition, the heat demand might be higher in the afternoon and evening hours, as the buffer tank needs to be recharged more frequently. Thus, the west façade is more likely to meet the simultaneous supply and demand requirement and thus achieve higher yields. The north facade acts as an environmental heat exchanger and has still significantly yields by approximately 80% of the east facade, 72% of the west facade, and 66% of the south facade, respectively.

4.2 Façade area

Fig. 9 shows the energy flows of the sources for different facade areas and orientations (east and west).

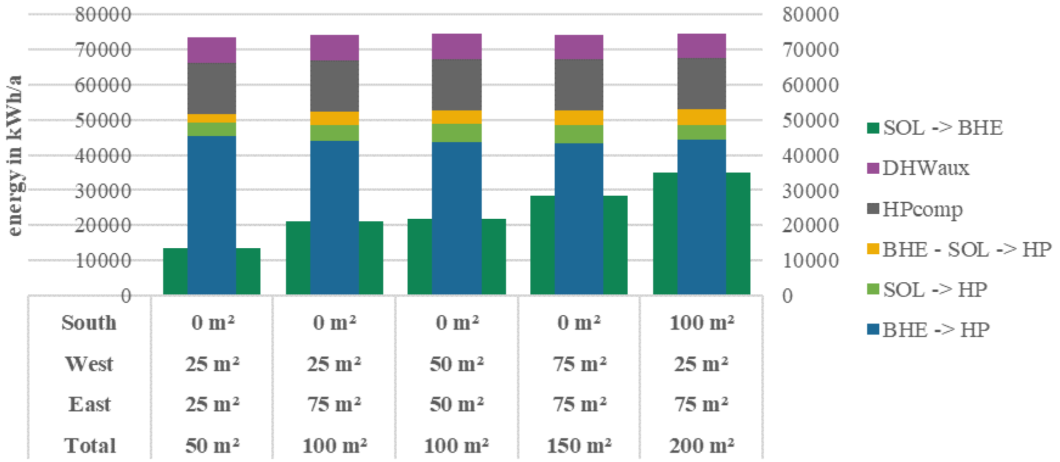


Fig. 9: Effect of different areas of the concrete facade for 6x100m borehole heat exchanger

For the same total area, the variant with a higher proportion of activated west façade shows higher yields. The larger the area of the solar facade, the more environmental heat can be used for the regeneration of the ground. At 100 m², about half of the heat extracted from the ground can be reloaded. By using a south facade, the proportion of the solar facade as a source for the heat pump is only minimally increased (compare 100 m² and 200 m²), but significantly more yield can be used for active regeneration of the ground. Since the source side of the heat pump has a limitation of the temperature range (-10 °C to 25 °C), other concepts are necessary for the use of the facade yields at higher temperature levels, e.g., due to orientation (south facade) or efficiency (darker concrete facade or facade materials made of glass or metal).

4.3 Façade color

Fig. 10 shows the effect of different efficiencies of the facade (zero-loss efficiency η_0) on the system performance. These can be achieved, for example, by different coatings or concrete colors that have different optical properties. For this purpose, specific spectrometric investigations were carried out in the project on small-format concrete samples.

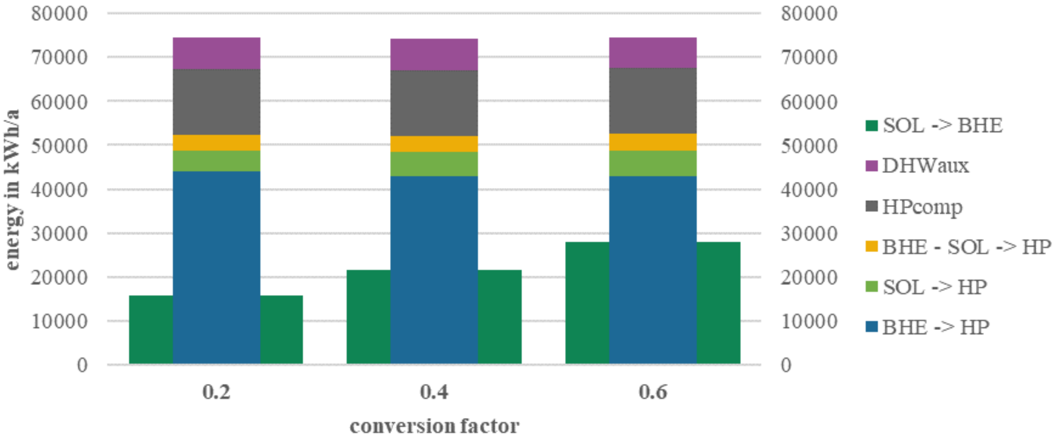


Fig. 10: Variation of the visual characteristics of the concrete facade, 6x100m borehole heat exchanger, 75 m² east and 30 m² west facade

A very light-colored facade exhibits a low (0.2), light-grey concrete, as planned in the demo object, exhibits a medium efficiency (0.4). In the implemented concept, the facade color has a significant influence on the amount of heat introduced into the ground for active regeneration but doesn't play an important role in the use as a source of the heat pump.

5. Conclusion and Outlook

The simulation results based on measured data of a concrete solar façade show the following effects on the considered heat pump system and operation mode:

- The amount of heat extracted from the ground can be significantly reduced.
- The remaining environmental heat is provided by the solar-thermal façade, whether as a sole source or in combination with the borehole heat exchanger.
- Most of the heat gained by the facade is used for the regeneration of the ground source.

By lowering the amount of extracted heat and by regenerating the ground source through a small thermally active façade, a reduction of the ground source of about 25% (either length or number of boreholes) can be achieved, compared to a system with a conventional rear-ventilated façade without impairing the heat pump performance. Higher efficiency can be achieved with larger activated areas or darker colors of the concrete claddings.

Such a system is currently implemented as a demonstration multi-family building in Southern Germany. Heating concepts for active facades with different claddings (e.g. metal and glass), operating over a larger temperature range, and considering direct loading of the buffer storage are currently being investigated. These concepts increase the complexity of the system, but can further reduce or even eliminate the ground source of the heat pump.

6. Acknowledgments

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Appendix

Tab. 4: collector parameters for basic equation according to Type 832 Haller et al., 2014

Quantity	Symbol	Unit
heat output of the collector per area	$\dot{q}_{out}$	W m^{-2}
latent (condensation + sublimation) heat gains	$\dot{q}_{lat}$	W m^{-2}
zero loss efficiency of the collector, sometimes referred to as η_0	$F'(\tau\alpha)$	-
incidence angle modifier for beam radiation	K_b	-
beam radiation incident on collector plane	I_b	W m^{-2}
incidence angle modifier for beam radiation	K_d	-
diffuse radiation incident on collector plane	I_d	W m^{-2}
factor for a wind dependency correction of F' (and thus the zero-loss coefficient $F'(\tau\alpha)$), used for unglazed collectors	$c_{w,\mathrm{F}'}$	s m^{-1}
wind speed parallel to the collector plane	u_w	m s^{-1}
first order heat loss coefficient	a_1	W K^{-1} m^{-2}
second order heat loss coefficient	a_2	W K^{-2} m^{-2}
arithmetic mean of the collector temperature	ϑ_m	°C
ambient temperature at location of collector field	ϑ_amb	°C
absolute ambient temperature at location of collector field	T_{amb}	K
wind speed dependency of heat losses	$c_{w,hl}$	J m^{-3} K^{-1}
long wave irradiation dependency of heat losses (or gains)	c_{IR}	-
long wave irradiation on collector plane	I_{IR}	W m^{-2}
Stefan Boltzmann constant	σ	W m^{-2} K
time	t	s
effective thermal capacitance of the collector (including fluid)	C_{eff}	J m^{-2} K^{-1}
wind speed from wind data	$u_{w,0}$	m s^{-1}
wind speed factor	wf	-
sky radiation factor	rf	-
long wavelength radiation downwards from sky	$I_{IR,0}$	W m^{-2}